

CAPACITY VALUE EVALUATION OF PHOTOVOLTAIC POWER GENERATION

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1. INTRODUCTION

Among the stochastic energy sources available in Japan, solar power is the most promising one in its existing quantity. As far as wind power, the suitable site where constant strong wind can be obtained throughout a year is limited to the specific areas — for example some islands — in Japan.

For this reason, the development of stochastic energy technologies has been focused especially on solar power, namely photovoltaic(PV) power generation. Recent technological progress of solar cell as well as peripheral equipments such as AC/DC inverter is remarkable and the cost of photovoltaic generation system has been also reduced considerably. The present target for the next development is to reduce by 2000 its generating cost to comparable level with electric price.

In the meantime, power companies are also beginning to show interests in PV generation being pushed by the current topic on green house effect. Actually, power companies in Japan have begun to purchase the power produced by PV generation or other renewable energy systems from April of this year. The price of the purchase has been set fundamentally the same as electricity price. In addition, they are planning to install PV systems in branch offices or in unutilized areas of conventional generating sites.

In our country, it is considered that PV system will be installed almost on the roof of individual houses because of site limitation. Under the situation of a little penetration of PV systems, the major subject in question is how to protect and control them which are interconnected to distribution feeder. And so far, this problem has been almost solved.

However, if PV generation is penetrated so extensively in future, it will affect on generation planning and system operation/control of power companies. Above

all, it is considered that the key issue will be the effect on generation planning.

Generally speaking, there exist two values for a generation facility: capacity value and energy value. As for the stochastic energy technologies like PV generation, the major concern is how much the capacity value of these technologies would be, compared with the conventional generating facilities.

Run-of-river hydro is a conventional generation facility which has stochastic nature. The cycle of output change of this type of generation is about one day at the shortest. On the other hand, the output of PV generation system may vary even in second due to, for example, cloud. Even if the net output is somewhat uniformed according to the number of installations in wide area, hourly change of its output should be taken into consideration at least.

It is the peculiar characteristic of electric demand in Japan that the peak demand is mostly formed by air conditioning load. In case of Tokyo Electric Power Company, which supplies electricity to the metropolitan area, the sensitivity of the electric demand with respect to the ambient temperature is about 1000MW/degree. This corresponds to the electricity generated by one large nuclear unit. Thus, the peak demand appears on the day when the sun is glaring and the temperature rises up. As the PV system is also expected to generate electricity in maximum power in such a case, it will contribute to the reduction of peak demand to some extent. Figure 1 shows the typical daily load curve and peak reduction by PV generation.

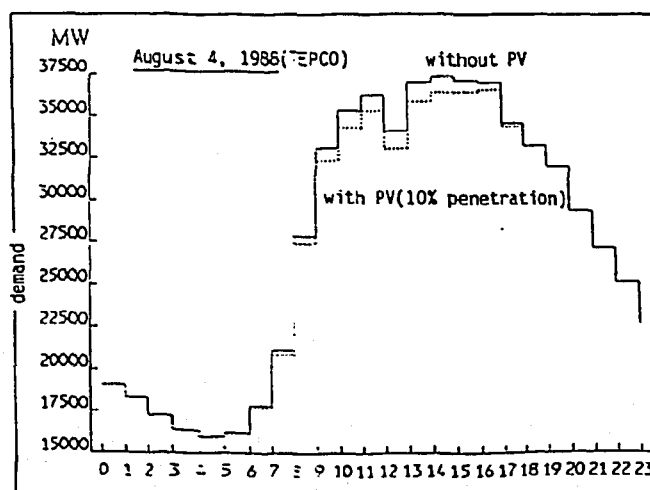


Figure 1.
Typical daily load curve.
(TEPCO)

Hence, to evaluate the value of PV generation, it is indispensable to take the correlation between electric demand and its output into consideration, as well as the inherent stochastic nature of its output due to the climate and the position of the sun.

The following chapter will present an example of capacity value(kW-value) evaluation of PV generation from power companies' generation planning point of view.

Before entering the main discussion, it is useful to review briefly the method actually applied to evaluate the supplying capability of conventional generation plants.

2. SUPPLYING CAPABILITY OF CONVENTIONAL PLANTS

2.1 Supplying Capability of Run-of-river Hydro.

Among the generating technologies of which output has nature dependency, run-of-river hydro is the only one that is incorporated in generation mix. In Japan, the supplying capability(capacity value) of run-of-river hydro is evaluated based on the following procedure:

First, a duration curve is made on which the actual daily outputs of the generation plant are plotted in decreasing order through a month. As shown in Figure 2, there exist two types of curves depending on the differences in averaging the past data. Specifically,

- Series curve: The actual daily generated power of the plant through a specific month is plotted in decreasing order for N years in a lump without considering time order. Then, every N data from left side of the N-year duration curve are averaged and the equivalent one month duration curve is derived.
- Parallel curve: The actual daily generated power of the plant is plotted through a specific month in decreasing order for N years separately. Then, N curves are averaged to make one equivalent duration curve.

Next, the lowest five data of each duration curve are averaged for the respective curves. This process produces P_{LS_s} and P_{LS_p} shown in Figure 2. Finally, the supplying capability of the run-of-river hydro is defined as the average of the above two values. Specifically,

$$P_{LS} = (P_{LS_s} + P_{LS_p}) / 2$$

This value is utilized in actual generation planning process.

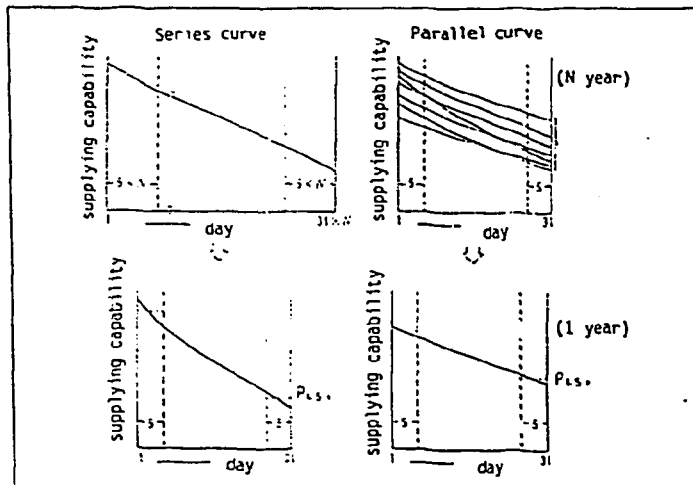


Figure 2.
Duration curve of
supplying capability
of run-of-river hydro.

2.2 Reserve Margin and Reliability of Supply in Generation Sector

The stochastic factors with which the planners of generation sector are confronted at the planning stage also include the fluctuation of electric demand and forced outage of generation plants. To deal with these factors, the probabilistic approach is adopted in evaluating the reliability of supply in generation sector. The method commonly utilized in Japan can be roughly summarized as follows.

As for the electric demand, the load duration curve shown in Figure 3 is utilized, in which the daily peak is plotted in decreasing order for a specific month. In our country, peak load appears in August in almost every power companies, this corresponds to the duration curve of daily peak load in August. If the shortage of supplying capacity occurs for some reason, it follows that the loss of load indicated in Figure 3 arises.

The stochastic nature of supplying capability is expressed by probability density function as shown in Figure 4. This curve is composed of three

stochastic factors: short term demand fluctuations, forced outage of a generation plant and nature dependency of a hydraulic generation plant. The last Curve is made from the process described in 2.1.

From both the duration curve of daily peak load(Fig.3) and the probability density function of supplying capability(Fig.4), the relation between reserve margin and loss of load expectation can be derived as shown in Figure 5. In Japan, power companies have been trying to keep the reserve margin equivalent to the loss of load expectation(LOLE) of 0.3 day/month. It should be noted here that the loss of load expectation is represented usually in terms of day/year, however in Japan it has been traditionally expressed in day/month.

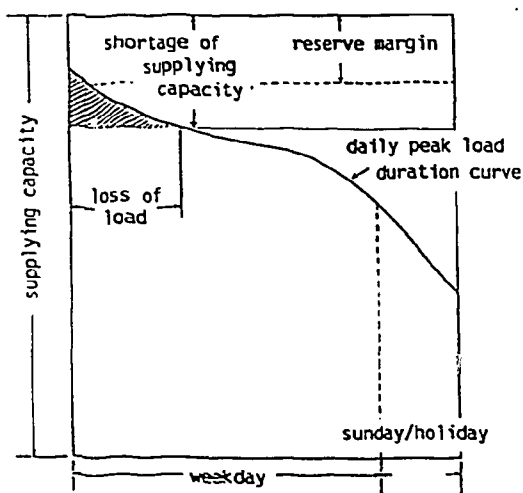


Figure 3. Daily load duration curve and loss of load.

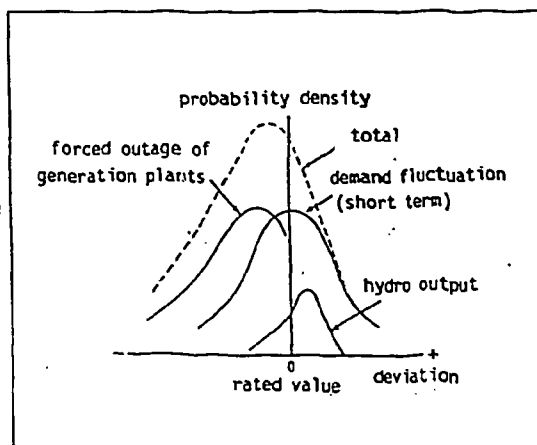


Figure 4. Probability density function of supplying capability.

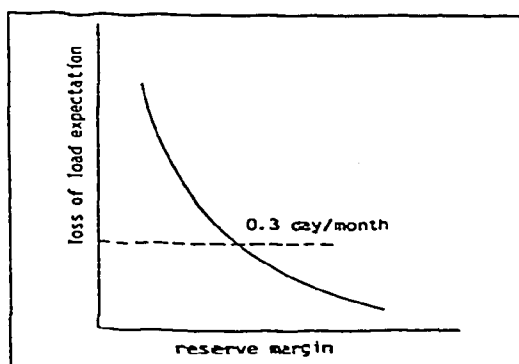


Figure 5. Reserve margin vs. LOLE.

In case of evaluating capacity value of PV generation, it is desirable to extend the above methodology. Because, by using the method which is familiar to the

planners, they can easily incorporate PV system into generating options under such future circumstances as PV system is penetrated in large quantity.

3. CAPACITY VALUE EVALUATION OF PHOTOVOLTAIC GENERATION

3.1 Insolation Data and Electric Demand Data

In order to evaluate the capacity value of PV generation, we should start from establishing the distribution characteristic of generated power, using insolation data of the specific area where PV systems are assumed to be installed. Here, it was assumed that the PV systems are installed within the supplying area of Tokyo Electric Power Company(TEPCO). The collected insolation data cover 10 years from 1981 to 1990. Five points shown in Figure 6 were selected as representatives of the whole area. Though the obtainable insolation data are restricted to hourly averaged ones, they will be sufficient for capacity value evaluation.

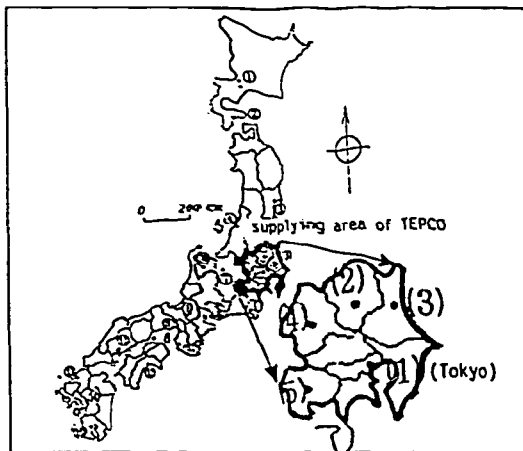


Figure 6.
Insolation data collecting point.
(1)-(5)

As previously stated, in Japan, there exists some correlation between the insolation and the electric demand during summer, the electric demand data are also necessary in evaluating supplying capability of PV generation. This point is different from conventional run-of-river hydro, where only the stochastic nature of the output is required in evaluating its capacity value. So, hourly electric demand data are also collected as for the corresponding 10 years.

3.2 Some Assumptions/Premises for the Evaluation

The evaluation was carried out based on the following assumptions/premises:

- The PV system is installed on the roof of a house, facing the south with an angle of inclination equal to the latitude.
- The unit capacity of PV system is fixed to 2.5kWp. This nearly corresponds to an average kw demand of a household in Japan.
- No battery system is installed and generated power can flow into the interconnected power companies' networks.
- The forced outage of PV system is not assumed.
- The electric demand data of 10 years are normalized so that the peak of each year coincides with each other, and so does the bottom.

3.3 Methodology for the Evaluation

The way of thinking for the capacity value evaluation of PV generation is based on the probabilistic approach conventionally applied in checking the adequacy of generation capacity. Specifically, the capacity value of PV generation is defined as the conventional generating capacity which could be reduced with keeping the loss of load expectation constant (0.3day/month).

Without PV generation, we can treat the supplying capability of generating facilities and the electric demand independently. The LOLE can be derived directly from the probability density function of supplying capability and the peak load duration curve which was given independently of generating facilities. However, it is impossible to do so under the existence of PV generation. With PV generation, it is necessary to revise beforehand the peak load duration curve itself by using the output of PV systems.

Once the revised duration curve is obtained, the same approach described in 2.2 can be utilized hereafter. Figure 7 shows the relations between reserve margin and loss of load expectation, for both cases with and without PV generation. The reserve margin which could be reduced by PV generation corresponds to its capacity value.

Four different methods applied here are described below. The differences among four methods lie in the ways to establish the peak load duration curve including PV generation.

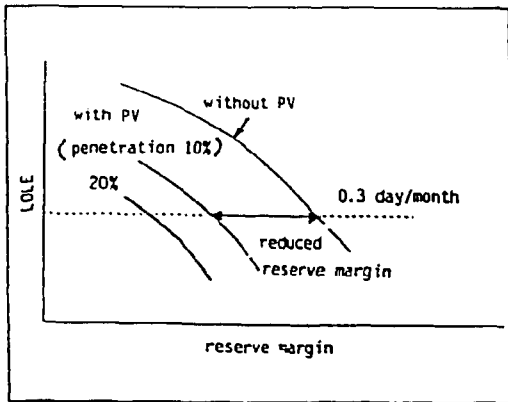


Figure 7.
Reduced conventional generating capacity (reserve margin)

(1) Series method:

Similarly to the case of making Series curve of run-of-river hydro's supplying capability, daily peak loads reduced by PV generation are firstly arranged for 10 years in decreasing order regardless of the year. Then, averaging every 10 data from the maximum point, we can obtain single curve which represents daily peak load of average summer (Figure 8).

(2) Parallel method:

In parallel method, the points of the same order in each year's duration curve (including PV generation) are averaged. Figure 9 illustrates its procedure.

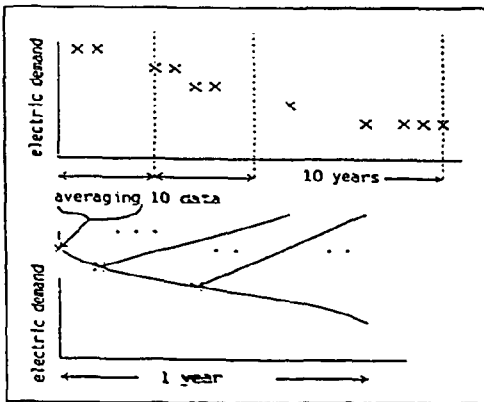


Figure 8. Series method.

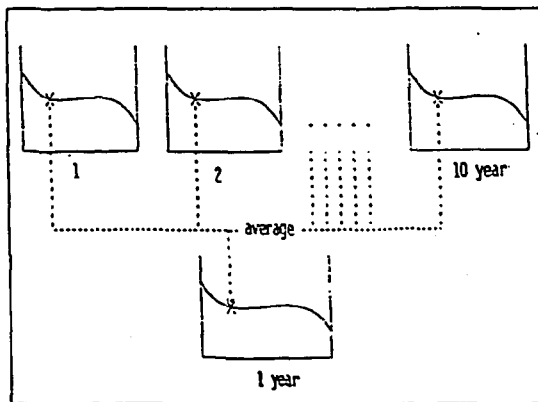


Figure 9. Parallel method.

(3) Direct method:

From practical point of view, not only the average but also the distribution is desired in order to evaluate precisely the capability of stochastic energy sources. In fact, even if considerable capacity value is perceived for PV generation as an average, it cannot be used as an alternative power source in

power systems if there exists little capacity value for particular year.

For this reason, the expected reductions of conventional generating capacity of each year, which would have been attained if PV generations had been introduced in that year, are calculated separately. The distribution of the capacity value in 10 years will be made clear at least in this way.

(4) Statistical method:

The method from (1) to (3) uses the past demand and PV output data directly. So, these methods are simple and easy to understand. However, it is difficult under these method to explain the differences of capacity value of PV generation among power companies or to consider its future trend.

To make general discussion, it is necessary to clarify beforehand the fundamental characteristics such as the relations between peak demand and PV output, by analyzing collected data statistically.

At least, the following two fundamental characteristics should be prepared in evaluating capacity value of PV generation. The first is the relation between electric demand and PV output, and the second is a distribution of the time of a day when peak demand appears. The demand peak usually shifts from daytime to evening as the total installed capacity increases.

The statistical method requires the following steps.

i) Categorization:

Electric demand is classified into 72(3×24) categories which correspond to each hour of weekday, Saturday and Sunday/holiday (nighttime is unnecessary in practice). It is enough to analyze the data only of July and August.

ii) Relation between electric demand and PV output

As shown in Figure 10, plot the relation between electric demand and PV output for each category. And make the probability density functions of

- PV output under given demand condition and,
- electric demand under given category.

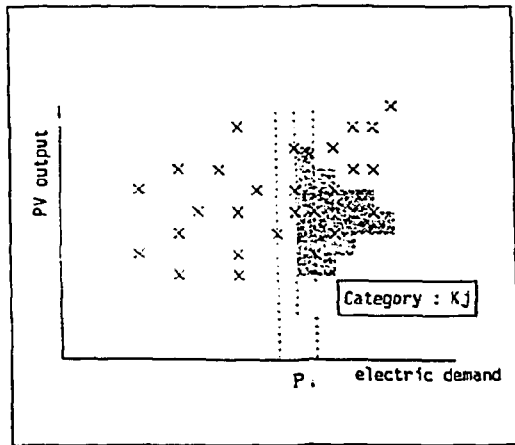


Figure 10.
Relation between electric demand and PV output.

iii) Electric demand revised by PV generation

The probability density function of electric demand including the PV output is established from the relations of ii). See Figure 11.

iv) Distribution of daily peak hour

The change of distributions of daily peak hour according to total installed capacity of PV generation is examined for weekday, Saturday and Sunday/holiday respectively (Figure 12).

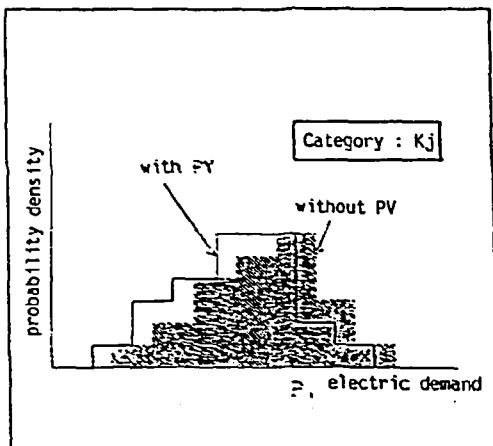


Figure 11.
Change of probability distribution of electric load by PV system installation

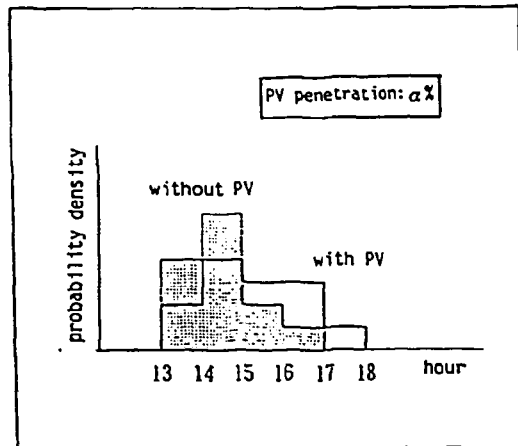


Figure 12.
Change of probability distribution of daily peak load.

v) Distribution of daily peak load

The probability density function of daily peak load including PV output is derived for 3 types of day (weekday, Saturday, Sunday/holiday) from the results of iii) and iv). Finally, the probability density function of daily peak load of average summer is constructed by weighting with the number of 3 types of day during summer time.

4. RESULTS

4.1 Series method

Figure 13 shows the daily peak load duration curve obtained by Series method. The horizontal axis corresponds to the number of days in July and August (62 days). The penetration of PV system is assumed from 0 to 30% and this means the percentage of houses with PV system to the total number of houses in the study area. The actual MW capacity and the rate to the peak demand are given in Table 1.

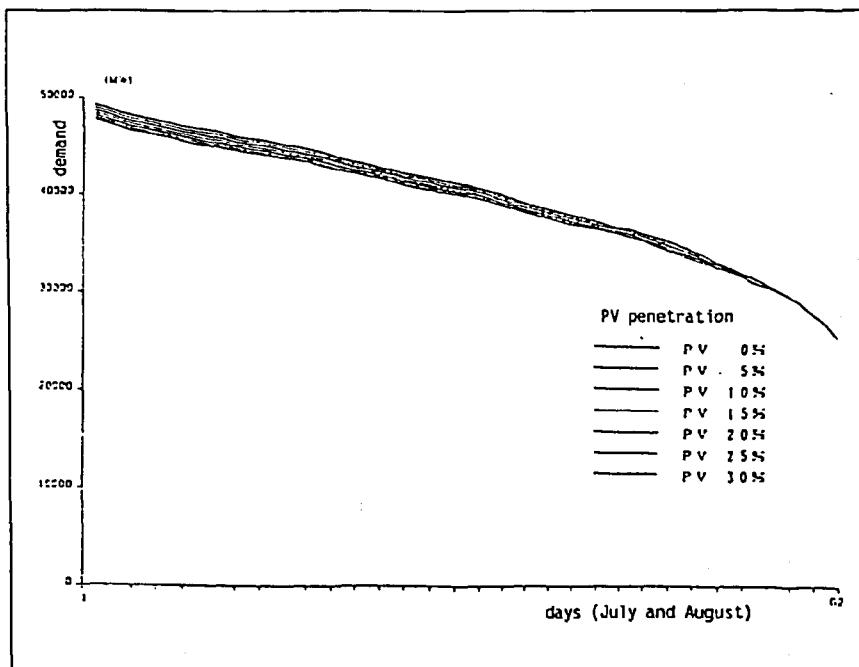


Figure 13. Daily peak load duration curve by Series method.

Table 1. Penetration rate and other index.

penetration rate	5	10	15	20	25	30	40	50	60	%
installed capacity	716	1432	2148	2865	3581	4297	5730	7162	8594	MW
installed cap. / peak demand	1.5	2.9	4.4	5.8	7.3	8.7	11.6	14.5	17.4	%

The relation between the reserve margin and the loss of load expectation is illustrated in Figure 14. About 1.3% reduction of the reserve margin can be accomplished under the condition of 10% penetration of PV generation with keeping LOLE of 0.3 day/month.

Details on the capacity value of PV system are described later, together with the results by other method.

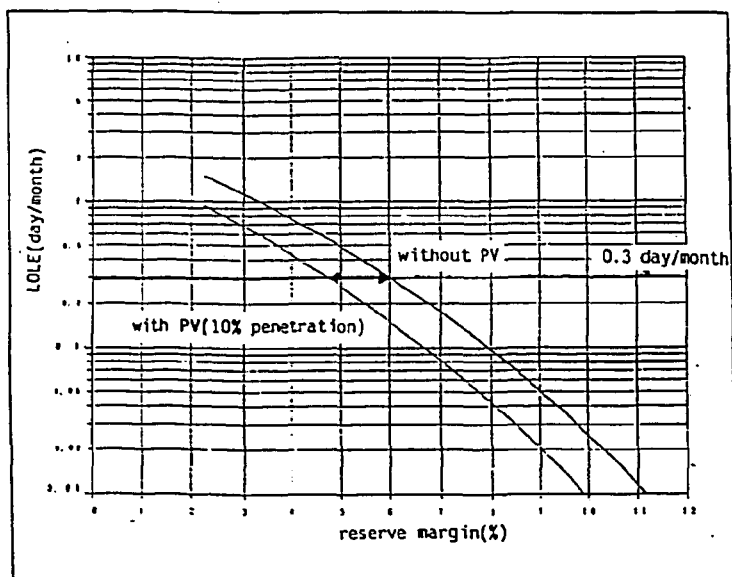


Figure 14.
Reserve margin vs. LOLE
(Series method)

4.2 Parallel method

An example of the daily peak load duration curve by Parallel method is shown in Figure 15. Little difference can be seen compared with Figure 14.

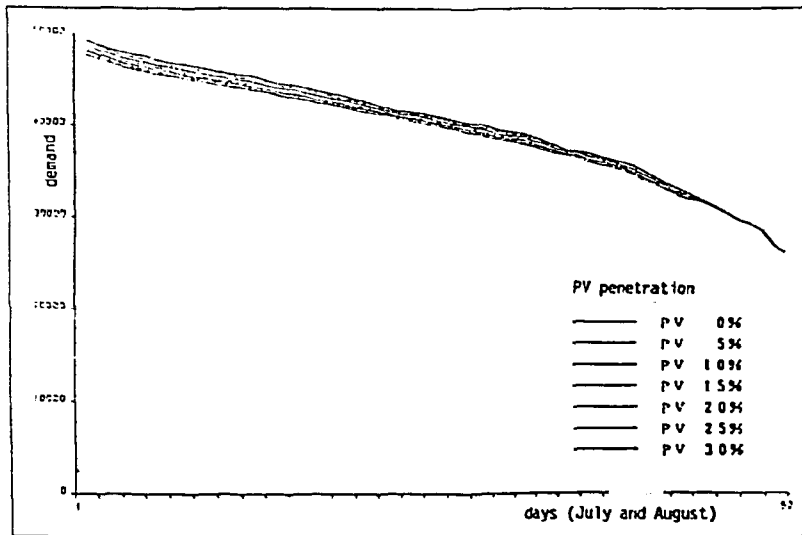


Figure 15.
Daily peak load duration curve by Parallel method

Under Series method, the demand data of the year when insolation is less than that of normal year are apt to gather near the left side of the curve. Therefore, there is a tendency that the capacity value gained by Series method is less than that by Parallel method.

4.3 Direct method

Figure 16 shows the capacity values calculated for each year from 1981 to 1990. Here, capacity value is expressed by,

$$\text{capacity value of PV generation (\%)} = \frac{\text{reduced conventional generation capacity}}{\text{total installed capacity of PV system}} \times 100$$

From this figure, we can find that the capacity values vary considerably with years especially when the total installed capacity of PV generation is small. Figure 17 shows the distribution of capacity value.

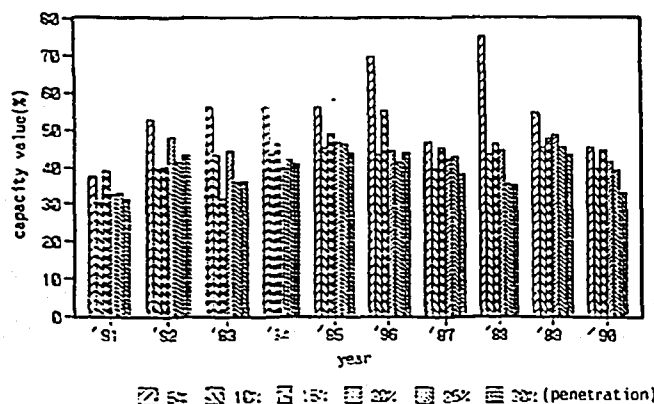


Figure 16.
Capacity value calculated for 10 years.

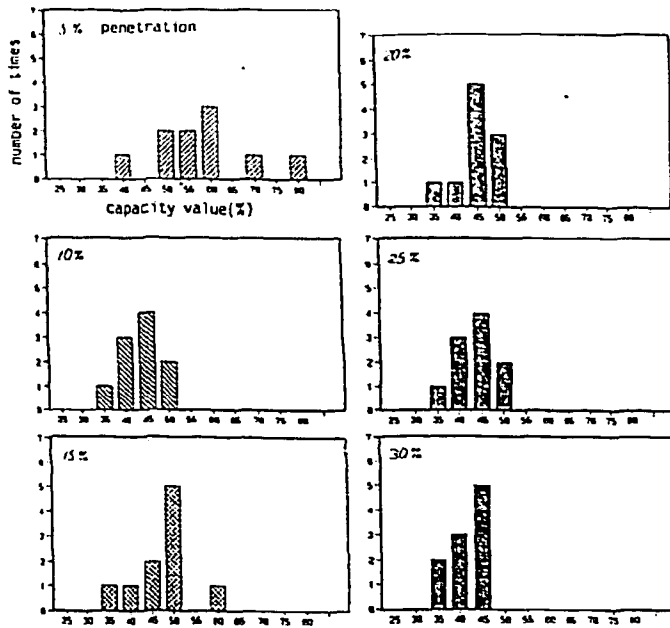


Figure 17.
Distribution of capacity value.

4.4 Statistical method

Figure 18 shows examples of the relation between electric demand and PV output. Generally speaking, there exists positive correlation between these two factors. However, it is true only for the case where the demand exceeds nearly 90% of the peak value.

Meanwhile, Figure 19 illustrates the distribution of daily peak hour. Daily peak load usually appears during 2 to 3 p.m. on weekday. As PV system increases in total quantity, daily peak hour shifts toward evening. This results in a saturation of PV capacity value of PV generation.

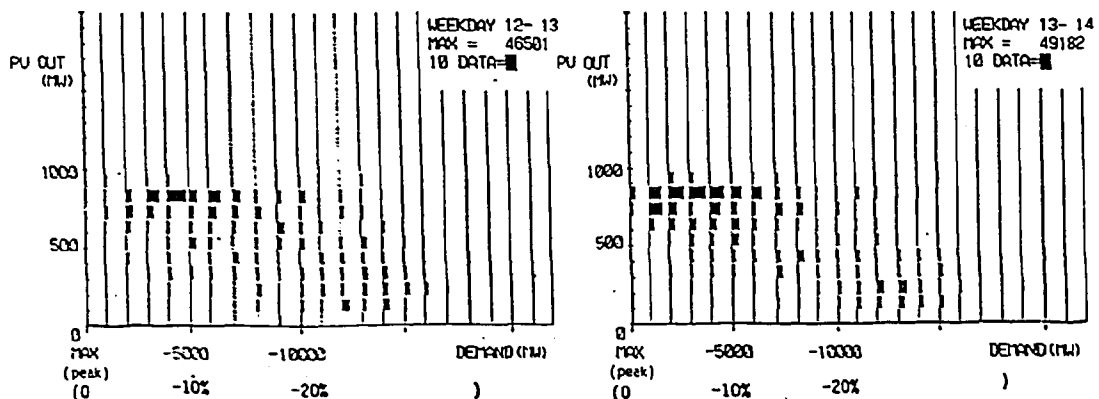


Figure 18. Correlation between electric demand and PV output.

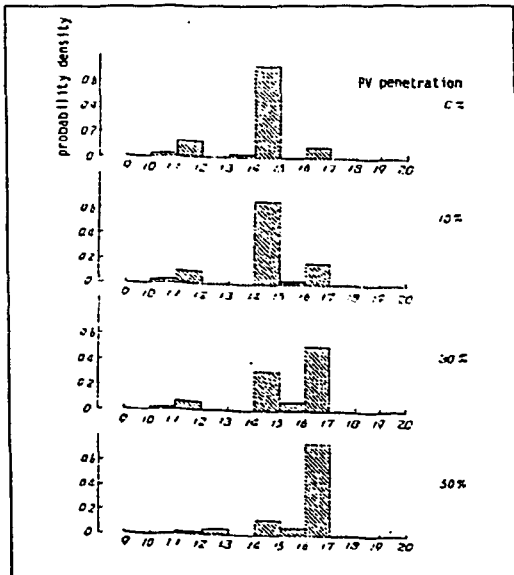


Figure 19.
Distribution of daily peak hour.

5. DISCUSSION AND CONCLUSION

The results obtained by above four different methods are summarized in Figure 20. Again, the capacity value is expressed as the ratio of reduced conventional generating capacity to total PV installed capacity. Except for the case of 5% penetration of PV system, the results of four method are almost the same. That is, within 30% penetration of PV system, the capacity value is estimated about 40 to 45% of its installed capacity.

Such a result holds true rigidly for the specific situation under the consideration. In fact, even in the same area, if the circumstance changes and the peak load appears also in winter for example — this tendency is coming true —, the capacity value of PV generation decreases about 15 to 20%. This has been confirmed by another study.

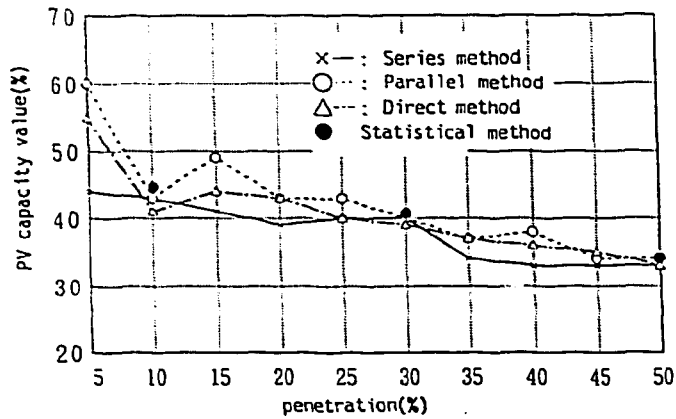


Figure 20. Comparison of the four applied method.

Meanwhile, the another value expected in PV systems, energy value, depends only on insolation, and it is constant regardless of total installed capacity. Therefore, the fuel savings of conventional generating facilities (thermal plants) can be accomplished in proportion to PV capacity.

Saturation, in one side, of the capacity value, and constancy, in the other side, of the energy value will lead to the optimal total installed capacity of PV systems from the view point of the national economy.

Figure 21 illustrates an example of such a study. The results are of course largely dependent upon the cost of PV system, and advantage of PV system is not perceived if the system cost is higher than ¥200,000/kw(\$1,600/kw ; \$1 = ¥125). In this study, it is assumed that the PV system will substitute conventional thermal plants. It is noted that special credits expected in PV system such as transmission/distribution credit and environmental credit and so forth are not included in this study.

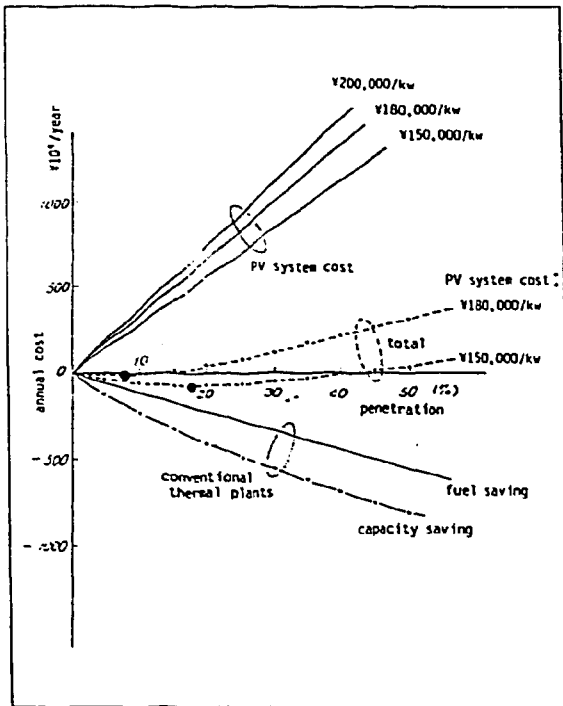


Figure 21.
Optimal PV penetration from the national economy.

As for the value/merit evaluation of the stochastic energy technologies, sufficient discussion has not been performed yet. So, there exists no evaluating methodology widely approved by the planners of electric companies.

Generating facilities having stochastic nature change their value according to the situation where they are applied. In future, it will become more and more important to move forward to the integrated resource utilization, with understanding the value/merit of renewable energy sources properly, from the aspects of efficient use of limited energy sources as well as global environment protection.